

Heavy Element Diffusion in Metal Poor Stars

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ABSTRACT

Stellar evolution models which include the effect of helium and heavy element diffusion have been calculated for initial iron abundances of $[\text{Fe}/\text{H}] = -2.3, -2.1, -1.9$ and -1.7 . These models were calculated for a large variety of masses and three separate mixing lengths, $\alpha = 1.50, 1.75$ and 2.00 (with $\alpha = 1.75$ being the solar calibrated mixing length). The change in the surface iron abundance for stars of different masses was determined for the ages 11, 13 and 15 Gyr. Iron settles out of the surface convection zone on the main sequence; this iron is dredged back up when the convection zone deepens on the giant branch. In all cases, the surface $[\text{Fe}/\text{H}]$ abundance in the turn-off stars was at least 0.28 dex lower than the surface $[\text{Fe}/\text{H}]$ abundance in giant-branch stars of the same age. However, recent high dispersion spectra of stars in the globular cluster NGC 6397 found that the turn-off and giant branch stars had identical (within a few percent) iron abundances of $[\text{Fe}/\text{H}] = -2.03$ (Gratton et al. 2001). These observations prove that heavy element diffusion must be inhibited in the surface layers of metal-poor stars. When diffusion is inhibited in the outer layers of a stellar model, the predicted temperatures of the models are similar to models evolved without diffusion, while the predicted lifetimes are similar to stars in which diffusion is not inhibited. Isochrones constructed from the models in which diffusion is inhibited fall half-way between isochrones without diffusion, and isochrones with full diffusion. As a result, absolute globular cluster ages which are based upon the absolute magnitude of the turn-off are 4% larger than ages inferred from full diffusion isochrones, and 4% smaller than ages inferred from no diffusion isochrones.

Subject headings: diffusion — globular clusters: individual (NGC 6397) — stars: evolution — stars: abundances — subdwarfs

1. Introduction

Atomic diffusion, whereby heavier elements settle relative to hydrogen in a star is a physical process which occurs in stars. Helioseismology provides clear evidence that diffusion is occurring in the Sun (e.g. Christensen-Dalsgaard, Proffitt, & Thompson 1993; Basu, Pinsonneault, & Bahcall 2000). As a result, a large number of studies have been made of the effect of diffusion on the evolution of the Sun and other stars (e.g. No-

erdlinger & Arigo 1980; Michaud, Fontaine, & Beaudet 1984; Michaud 1986; Deliyannis & Demarque 1991; Chaboyer & Demarque 1994; Vauclair & Charbonnel 1995; Salaris, Groenewegen, & Weiss 2000; Salaris & Weiss 2001). Models and isochrones appropriate for globular cluster stars have shown that the inclusion of diffusion reduces the main sequence life time of the stars and reduces their effective temperatures. The absolute age inferred for the oldest globular clusters is reduced by $\sim 7\%$ when diffusion is included in the

stellar models (Chaboyer 1995).

Diffusion leads to changes in the surface abundances of elements. In particular, the abundances of elements heavier than hydrogen will decrease over time. The characteristic time scale for the depletion of an element out of the surface of a star is given by (Michaud, Fontaine, & Beaudet 1984)

$$\tau \simeq K \frac{M_{CZ}}{MT_{CZ}^{3/2}} \quad (1)$$

where M is the total mass of the star, M_{CZ} is the mass of the surface convection zone, T_{CZ} is the temperature at the base of the convection zone and K is a constant, which can vary for different elements. Since M_{CZ} can be a strong function of the total mass of the star, the diffusion models predict that the surface abundances vary for stars of different masses.

Observations of Li in metal-poor stars have shown the existence of a plateau, where the abundance is constant over a wide range of effective temperatures and metallicities (e.g. Spite & Spite 1982; Thorburn 1994; Ryan, Norris, & Beers 1999). These observations suggest that diffusion is inhibited near the surface of metal-poor stars (e.g. Michaud, Fontaine, & Beaudet 1984; Deliyannis & Demarque 1991; Chaboyer & Demarque 1994). However, Salaris & Weiss (2001) have shown that the Li abundance observations can be reproduced by models which include fully efficient diffusion. This follows from their analysis which includes the effects of observational errors, uncertainties in the Li abundance determinations and in the effective temperature scale, and the size of the observed samples of stars. Li is one of three elements produced during the big bang, and so its primordial abundance is of considerable importance in constraining big bang nucleosynthesis. Salaris & Weiss (2001) found that, due to diffusion, their predicted primordial Li abundance was a factor of two higher than that observed in the metal-poor plateau stars.

The inclusion of diffusion in stellar models has important consequences for the estimated age of the oldest globular clusters and the inferred primordial Li abundance. Thus, it is important to determine if diffusion is actually occurring in metal-poor stars. The recent observations of iron abundances in turn-off and giant branch stars in the metal-poor globular cluster NGC 6397 by Grat-

ton et al. (2001) provide an excellent test for the occurrence of diffusion in metal-poor stars. Gratton et al. (2001) found that the turn-off and giant branch stars had identical iron abundances (within a few percent). Stars near the turn-off can have convective masses which are orders of magnitude smaller than those on the giant branch. Thus, one would have expected that if diffusion does occur near the surface of metal-poor stars, it would lead to a marked difference in the surface abundance of iron between the main sequence turn-off stars, and those in the giant branch. These effects should be particularly noticeable in NGC 6397 because it is a relatively metal-poor cluster with $[\text{Fe}/\text{H}] = -2.02 \pm 0.04$ Gratton et al. (2001). The convective envelope masses on the main sequence become smaller as one goes to more metal-poor stars; as a result, the diffusion time scale (equation 1) is shorter for metal-poor stars.

The use of iron abundances in globular clusters to study diffusion has several advantages over using Li observations in field halo stars. First, all the stars in NGC 6397 were born with the same initial composition and at the same time ¹. Li abundances are usually determined for field halo stars which have different compositions, and may have different ages. Second, the interpretation of the Li observations is complicated by the fact that Li is destroyed at temperatures $T \gtrsim 2.5 \times 10^6$ K, implying that mixing or turbulence within a star can lead to a change in the surface abundance of Li. In contrast, mixing or turbulence can only change the surface abundance of iron if diffusion is already operating; otherwise the abundance of iron is the same everywhere in the star and mixing cannot change the surface abundance of iron. Finally, iron abundance measurements are typically determined from a large number of lines, minimizing the observational errors. Li abundances are determined from a single line, and the Li abundance measurements are quite sensitive to the adopted effective temperature scale.

Section 2 of this paper discusses the stellar models and isochrones used in this study. This includes fits of the isochrones to the observed color

¹The spectroscopic observations of Gratton et al. (2001) and Castillo et al. (2000) have found no star to star abundance variations among the giant branch stars. Photometric studies (Alcaino et al. 1997) show a single turn-off which indicates that all of the stars in NGC 6397 have the same age.

magnitude digram of NGC 6397. The effects of metal diffusion on the surface abundance of iron are presented in §3, where it is concluded that diffusion must be inhibited in the surface layers of metal-poor stars. The impact of inhibiting the diffusion on the derived ages of globular clusters is explored in §4. Finally, §5 contains a summary of the principal results in this paper.

2. Stellar Models and Isochrones

The stellar evolution models were calculated using Chaboyer’s stellar evolution code. The basic input physics used in the code is described in Chaboyer, Green, & Liebert (1999), with the exception of the atomic diffusion coefficients. These calculations use the Thoul, Bahcall, & Loeb (1994) diffusion coefficients for helium and heavy elements. The variation of the abundances of H, He and Fe are followed, all other heavy elements are assumed to diffuse at the same speed as fully-ionized iron. The differences in the diffusion velocities among the heavy elements are small for the low mass stars ($M \leq 0.9 M_{\odot}$) considered here (Turcotte, Richer, & Michaud 1998), and our procedure does not introduce any significant error into the calculations. The local changes in the metal abundance are taken into account in the opacity computation by interpolating among tables with different heavy element mass fractions (Z).

Note that the Thoul, Bahcall, & Loeb (1994) diffusion coefficients do not include the effects of radiative acceleration. Studies of the effects of radiative acceleration on solar metallicity F-stars have been performed by Richer et al. (1998) and Turcotte, Richer, & Michaud (1998). These studies have shown that radiative acceleration is predicted to be important for solar metallicity stars with masses greater than approximately $1.2 M_{\odot}$. The importance of radiative acceleration depends on the opacity (which is a function of temperature and density) and the radiative flux. In general the physical conditions near the base of the surface convection zone in a $M = 0.80 M_{\odot}$ metal-poor star are similar to those in a $M = 1.2 M_{\odot}$ solar metallicity star. As a result, it is unlikely that radiative acceleration is important in the stars which we will model in this paper. Furthermore, if radiative acceleration was important, the surface abundances of the elements would be effected, leading

to large abundance anomalies (Turcotte, Richer, & Michaud 1998). Such abundance anomalies are not observed.

A calibrated solar model was calculated by adjusting the initial mixing length, Z , and the helium abundance in the model until a $1.0 M_{\odot}$ model yielded the correct solar radius, luminosity and a surface $Z/X = 0.0245$ (Grevesse & Noels 1993) at the solar age (assumed to be 4.6 Gyr). The calibrated solar model had a mixing length of $\alpha = 1.75$; an initial heavy element mass fraction of $Z = 0.02$ and an initial helium abundance of $Y = 0.275$. At 4.6 Gyr, the model had a surface $Z = 0.0179$ and $Y = 0.249$. This value for the present day value of Y is in good agreement with helioseismic helium-abundance determinations which find $Y = 0.24 - 0.25$ (Basu 1998; Richard et al. 1998). The base of the convection zone is located at $R = 0.716 R_{\odot}$ in the model, which is a similar to the depth inferred from helioseismology of $R = 0.713 R_{\odot}$ (Basu 1998).

The metal poor stellar models were calculated for four different initial Fe abundances: $[\text{Fe}/\text{H}] = -2.3, -2.1, -1.9$ and -1.7 . The α -capture elements were assumed to be uniformly enhanced by 0.2 dex, which is similar to the observed value in NGC 6397. Gratton et al. (2001) found $[\text{O}/\text{Fe}] = +0.21 \pm 0.05$ in their high dispersion study of NGC 6397. As α -element enhanced low temperature opacities were not available to us, a scaled solar composition was used in the calculations. The effect of α -element enhancement was taken into account by changing the relationship between Z and $[\text{Fe}/\text{H}]$ (Salaris, Chieffi, & Straniero 1993). Salaris, Chieffi, & Straniero (1993) showed that most of the evolutionary properties of metal poor stars with enhanced α -capture elements could be reproduced by models with scaled solar compositions if the total heavy element mass fraction Z was identical in the two sets of models. By calculating models over a relatively large range in $[\text{Fe}/\text{H}]$ we can explore what effect possible mismatches between the observed abundances and those used in our models have on predictions.

The helium abundance in the models was determined assuming a primordial helium abundance of $Y_p = 0.245$ and $\Delta Y/\Delta Z = 1.5$. The primordial helium abundance was chosen to be in agreement with Burles et al. (1999) who base their determinations upon big bang nucleosynthesis and deu-

terium abundance measurements in quasars. The value of $\Delta Y/\Delta Z$ was determined using Y_p and the solar values of initial Y and Z from the models.

In order to investigate how uncertainties in the treatment of convection affect the results, models were calculated for three different values of the mixing length, $\alpha = 1.50, 1.75$ and 2.00 (recall that $\alpha = 1.75$ is the solar calibrated mixing length). Models with masses ranging from $M = 0.5 - 0.9 M_\odot$ were evolved to ages of 11, 13 and 15 Gyr. The mass spacing ranged from $0.01 M_\odot$ to $0.001 M_\odot$. In total, over 4000 stellar evolution runs were calculated. The age range of 11 – 15 Gyr was chosen, as it encompasses the most recent estimate for the absolute age of old, metal-poor globular clusters, 13.2 ± 1.5 Gyr (Chaboyer 2001).

As a test of the models, isochrones were calculated using the stellar models which included the effects of diffusion and fit to the NGC 6397 color-magnitude observations of Alcaïno et al. (1997). The isochrones were constructed in manner described by Chaboyer, Green, & Liebert (1999). In performing the isochrone fits, the distance modulus and reddening were varied until the best fit to the unevolved main sequence was obtained. The reddening was constrained by the study of Anthony-Twarog & Twarog (2000) who obtained *uvby*H β photometry of NGC 6397 and found $E(B - V) = 0.179 \pm 0.003$ mag. In fitting the theoretical isochrones to the observed data, the reddening was allowed to vary by $\pm 2\sigma$ from the value determined by Anthony-Twarog & Twarog (2000). The distance scale to globular clusters is still a matter of considerable debate (e.g. Chaboyer 2001) and, as a result, the distance modulus was allowed to vary by ± 0.15 mag. Some samples of the isochrone fits are shown in Figure 1. In general, an age of 11 Gyr was found for NGC 6397. The best fitting isochrones had temperatures at the turn-off ranging from $T_{\text{eff}} = 6460$ to 6630 K. Based upon the H α profiles in their high dispersion spectra, Gratton et al. (2001) estimated the temperature of the turn-off stars to be $T_{\text{eff}} = 6576 \pm 90$ K, which is in good agreement with the models.

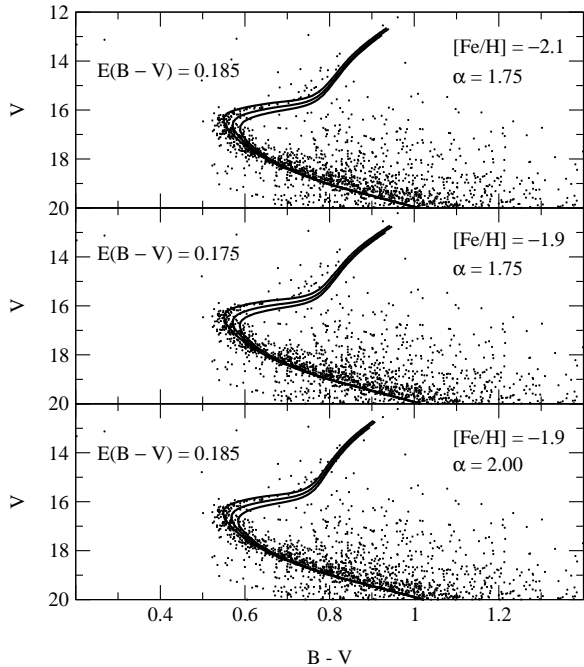


Fig. 1.— Isochrone fits to the NGC 6397 photometry of Alcaïno et al. (1997) for different values of $[\text{Fe}/\text{H}]$ and the mixing length α . All panels show 11 (bluest turn-off), 13 and 15 Gyr isochrones. A distance modulus $(m - M)_V = 12.60$ was used in all of the fits.

3. Metal Diffusion Results

The principal results of this paper are shown in Figures 2 – 3 which show the change in the surface iron abundance as a function of $\log g$ (Figure 2) and the effective temperature (Figure 3). Since stars on the giant branch and on the main sequence can have the same effective temperatures, it is easiest to illustrate the effects of heavy element diffusion on the surface iron abundance when the surface $[\text{Fe}/\text{H}]$ value is plotted as a function of $\log g$ (Figure 2). The lowest mass stars (which are on the main sequence) have the highest surface gravities. As one goes to lower surface gravities (to the right in the figure), the stars are more and more massive. Low mass main sequence stars have fairly large convection zones. As a result, the time scale for the diffusion of metals out of the surface convection zone is very long resulting in little change in the surface abundance of iron. The higher mass stars on the main sequence have less

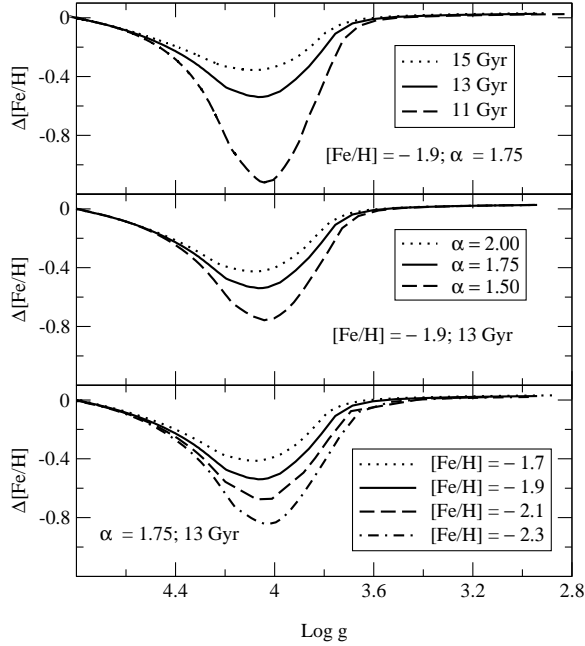


Fig. 2.— The change in the surface $[\text{Fe}/\text{H}]$ as a function of $\log g$ for different ages (top panel), mixing lengths (middle panel) and values of initial $[\text{Fe}/\text{H}]$ (bottom panel). The solid line is the same in all of the panels (initial $[\text{Fe}/\text{H}] = -1.9$; $\alpha = 1.75$; 13 Gyr). Main sequence stars are on the left of this diagram, while red giant branch stars are on the right.

massive surface convection zone, leading to shorter diffusion time scales and a larger depletion of iron at the surface. The maximum depletion in the surface $[\text{Fe}/\text{H}]$ abundance occurs around the main sequence turn-off, where the depth of the convection zone is at a minimum. As stars evolve past the turn-off point, their convection zone rapidly deepens, dredging up the iron which had diffused out of the surface convection zone on the main sequence. As a result, the surface iron abundance returns to its initial value on the giant branch ($\log g \lesssim 3.6$).

The top panel in Figure 2 illustrates how the depletion of $[\text{Fe}/\text{H}]$ varies as a function of the assumed age of NGC 6397. If NGC 6397 is 11 Gyr old (as suggested by the isochrone fits), then the turn-off stars have a mass of $M \simeq 0.80 M_{\odot}$ and during their main sequence lifetime have an average convective envelope mass of around $M_{\text{CZ}} \sim 1 \times 10^{-3} M_{\odot}$ leading to large depletions in $[\text{Fe}/\text{H}]$

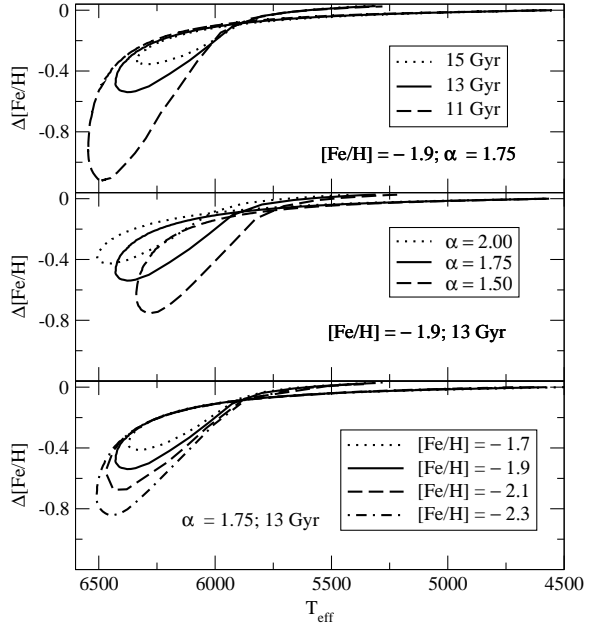


Fig. 3.— The change in the surface $[\text{Fe}/\text{H}]$ as a function of effective temperature for different ages (top panel), mixing lengths (middle panel) and values of initial $[\text{Fe}/\text{H}]$ (bottom panel). The solid line is the same in all of the panels (initial $[\text{Fe}/\text{H}] = -1.9$; $\alpha = 1.75$; 13 Gyr). Cool main sequence stars are on the extreme right of this diagram, while red giant branch stars are located slightly above the main sequence stars for $T_{\text{eff}} \lesssim 5800$ K.

in the turn-off stars. In contrast, 13 Gyr turn-off stars have a mass of $M \simeq 0.76 M_{\odot}$ and during their main sequence lifetime have a convective envelope mass which is about 3 times as massive as a $M \simeq 0.80 M_{\odot}$ star. As a consequence, if NGC 6397 is really 13 Gyr old, then the predicted $[\text{Fe}/\text{H}]$ depletion at the surface is substantially smaller than if it is 11 Gyr old. In general, older ages for globular clusters imply that the effects of atomic diffusion are smaller.

The middle panel in Figure 2 illustrates how the depletion of $[\text{Fe}/\text{H}]$ varies as a function of the mixing length assumed in the models. Lower values of the mixing length lead to less massive convection zones on the main sequence. As a result, the time scale for diffusion is shorter in models with lower mixing lengths, leading to larger depletions of the surface iron abundance. Finally, the bot-

tom panel in Figure 2 illustrates the effect that changing the initial $[\text{Fe}/\text{H}]$ abundance has on the predicted $[\text{Fe}/\text{H}]$ depletions. As is well known, the higher the heavy element abundance, the higher the opacities are (e.g. Rogers & Iglesias 1992) leading to more massive convection zones and less depletion in the surface iron abundance.

The effective temperature of a star can be determined from observations much more accurately than its surface gravity. As a result, our model calculations are best compared to observations using temperature as the independent variable. This is shown in Figure 3 which plots the change in the surface $[\text{Fe}/\text{H}]$ abundance as a function of T_{eff} . Of course, stars on the giant branch and the main sequence may have the same temperatures, and so the depletion lines are double value functions. The lowest mass models on the main sequence are located at the lowest effective temperatures (extreme right) in Figure 3. It turns out that even the lowest mass models we evolved had less massive convection zones than the models on the giant branch. As a consequence, the surface iron abundance is somewhat higher (~ 0.04 dex) in the cool giant branch models ($T_{\text{eff}} \lesssim 5800$ K) than in the main sequence models. Note that the difference in surface $[\text{Fe}/\text{H}]$ between turn-off stars and giant branch stars in the models plotted in Figure 3 is always greater than 0.3 dex.

Gratton et al. (2001) determined the temperature of the main sequence turn-off stars to be $T_{\text{eff}} = 6476 \pm 90$ K, while the giant branch stars they observed had $T_{\text{eff}} = 5478 \pm 60$ K. For the iron abundances Gratton et al. (2001) found that the turn-off stars had $[\text{Fe}/\text{H}] = -2.02 \pm 0.01$, while the giant branch stars had $[\text{Fe}/\text{H}] = -2.05 \pm 0.03$. The quoted errors are internal, given by the standard deviation in the mean for each group of stars. In terms of possible systematic errors between the two $[\text{Fe}/\text{H}]$ measurements, this is likely to be dominated by uncertainties in the adopted temperatures. Gratton et al. (2001) show that for the turn-off stars, their error of ± 90 K in the temperature translates into an error of ± 0.09 dex. For the giant branch stars, their error of ± 60 K in temperature translates into an error of ± 0.06 dex. Adding these errors in quadrature, one can conclude that the difference in the iron abundance between the giant branch and turn-off stars is $\Delta[\text{Fe}/\text{H}] = 0.03 \pm 0.11$ dex.

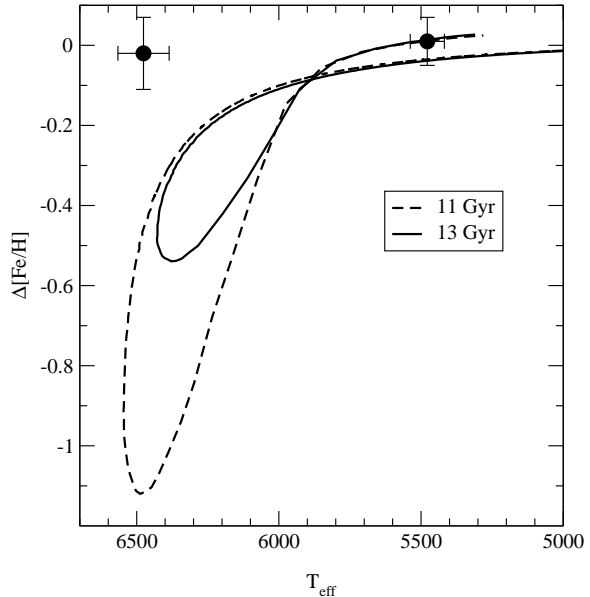


Fig. 4.— The change in the surface $[\text{Fe}/\text{H}]$ in the models (solid line with initial $[\text{Fe}/\text{H}] = -1.9$, mixing length $\alpha = 1.75$ and an age of 13 Gyr) is compared to the observations of turn-off and sub-giant branch stars in the globular cluster NGC 6397 (Gratton et al. 2001). The models clearly do not match the observed data.

In order to obtain a best estimate for the predicted $\Delta[\text{Fe}/\text{H}]$ between the giant branch and turn-off stars, the models with initial iron abundances of $[\text{Fe}/\text{H}] = -1.9$ and -2.1 were searched to determine which cases had turn-off stars in the $\pm 1\sigma$ range given by Gratton et al. (2001) ($T_{\text{eff}} = 6386 - 6556$). For each set of models, $\Delta[\text{Fe}/\text{H}]$ was determined by taking the difference in $[\text{Fe}/\text{H}]$ between the turn-off stars and those stars on the giant branch which were 1000 K cooler than the turn-off stars. The results are shown in Table 1. The predicted $\Delta[\text{Fe}/\text{H}]$ values ranged from 0.31 dex to 2.56 dex, with an average of 0.77 dex. The minimum predicted change in $[\text{Fe}/\text{H}]$ between the giant branch and the turn-off stars is 2.5σ larger than the observed difference. The lowest $\Delta[\text{Fe}/\text{H}]$ values occur for the 15 Gyr models; however as discussed in the previous section the 15 Gyr isochrones do not fit the observed color-magnitude diagram. For models 13 Gyr or younger, the minimum predicted $\Delta[\text{Fe}/\text{H}] = 0.41$ dex, which is 3.5σ larger than observed. The difficulty in match-

TABLE 1
DIFFERENCE IN $[\text{Fe}/\text{H}]$ BETWEEN TURN-OFF AND GIANT BRANCH MODELS

Initial $[\text{Fe}/\text{H}]$	Age (Gyr)	α	$\Delta[\text{Fe}/\text{H}]$
-1.9	11	1.50	1.58
-1.9	11	1.75	0.92
-1.9	13	1.75	0.50
-1.9	13	2.00	0.41
-1.9	15	2.00	0.31
-2.1	11	1.50	2.56
-2.1	13	1.50	0.79
-2.1	13	1.75	0.57
-2.1	13	2.00	0.45
-2.1	15	2.00	0.33

ing the observed $[\text{Fe}/\text{H}]$ values is shown in Figure 4 which compares models which had an initial $[\text{Fe}/\text{H}]$ of -1.9 , age of 13 Gyr and a mixing length of $\alpha = -1.75$ to the data from Gratton et al. (2001).

An examination of Figure 2 shows that the minimum possible depletion will occur in the 15 Gyr, $\alpha = 2.00$ models which had an initial iron abundance of $[\text{Fe}/\text{H}] = -1.7$. These models have a turn-off temperature of $T_{\text{eff}} = 6361$ K, which differs by 1.3σ from the observed value, and a giant branch $[\text{Fe}/\text{H}]$ which differs from the observed value by 3σ . In this extreme case, the predicted change in $[\text{Fe}/\text{H}]$ between the turn-off and giant branch is $\Delta[\text{Fe}/\text{H}] = 0.28$ dex, which is 2.3σ different from the observed value. Since all of the models differ by more than 2σ from the observations, we conclude that heavy element diffusion does not occur near the surface of metal-poor stars.

4. Discussion

Observations of Li in metal-poor field stars have suggested for some time that diffusion is inhibited near the surface of metal-poor stars (e.g. Michaud, Fontaine, & Beaudet 1984; Deliyannis & Demarque 1991; Chaboyer & Demarque 1994). However, Salaris & Weiss (2001) have pointed out that when one takes into account the observational errors, uncertainties in the Li abundance determinations and in the effective temperature scale, and the size of the observed samples of stars,

the Li abundance observations can be reproduced by models which include fully efficient diffusion. In contrast, observations of iron abundances in turn-off and giant branch stars in the metal-poor globular cluster NGC 6397 clearly show that heavy element diffusion does not occur near the surface of metal-poor stars.

A key difference between the Li observations analyzed by Salaris & Weiss (2001) and the Fe observations analyzed here is that the Li observations are primarily obtained for field stars, while the Fe abundances which have been analyzed in this paper have been obtained for a single globular cluster. Evolutionary time scales near the main sequence turn-off are much more rapid than on the main sequence. As a result observations of random field stars are biased against finding stars near the turn-off. It is stars at the turn-off in which diffusion causes the greatest depletion of Li. Hence, observations of field stars are biased against finding Li depleted stars. The Monte Carlo simulations of Salaris & Weiss (2001) show that even if Li diffusion occurs at the surface of metal-poor stars, observational selection effects imply that one is unlikely to observe stars with large Li depletions, given the size of present day samples. Salaris & Weiss (2001) found that three times as many stars as are in the current datasets must be observed in order for the observational data to show clear signs of Li depletion at hot temperatures. In contrast, Gratton et al. (2001) were able to use the observed

color-magnitude diagram of NGC 6397 to select turn-off stars for spectroscopic study. Hence, these observations are a much cleaner test for the presence of diffusion than the field star Li abundance measurements analyzed by Salaris & Weiss (2001).

Iron is not subject to depletion on the red giant branch making it easy to compare the observed iron abundances between the main sequence turn-off and giant branch in a given cluster. The deepening of the convection zone on the red giant branch leads to significant Li depletion in these stars. The globular cluster Li abundance data analyzed by Salaris & Weiss (2001) involved a comparison between giant branch stars and main sequence turn-off stars. As the giant branch stars undergo significant Li depletion these observations do not serve as strong constraints on the presence of diffusion. As a result, there is no conflict between the study of Salaris & Weiss (2001) and this study. Salaris & Weiss (2001) simply claim that the available Li data do not rule out the presence of diffusion near the surface of metal-poor stars. The iron abundances measurements analyzed in this paper are much more sensitive to the presence of diffusion than the Li observations. Hence, the present observational data shows that diffusion is inhibited near the surface of metal-poor giant branch stars.

Two mechanisms which inhibit diffusion in the surface layers of stars are modest amounts of mass loss (Vauclair & Charbonnel 1995) and mixing induced by rotation (e.g. Vauclair 1988; Pinsonneault, Deliyannis, & Demarque 1992; Pinsonneault, et al. 1999). The wind loss models require that the mass loss in low mass metal-poor stars be an order of magnitude larger than is observed in the Sun. Observations of a correlated depletion of Lithium and Beryllium in Population I F stars suggest that rotationally induced mixing, and not mass loss is operating in these stars (Deliyannis et al. 1998).

Mixing induced by rotation suppresses diffusion by effectively increasing the mass of the surface mixed zone, leading to longer time scales for the depletion of elements at the surface of the star (cf. equation 1). Using equation (1) as a guide, we may estimate the mass of the surface mixed zone in metal-poor stars by requiring that the surface abundance of iron change by less than 0.1 dex in 13 Gyr. The constant K in equation (1) was cal-

culated for our models, and from this, we estimate that the mixed zone at the surface of a metal-poor star has a mass $M_{mix} \gtrsim 0.005 M_{\odot}$. In contrast, the convection zone masses in turn-off stars with $[\text{Fe}/\text{H}] \simeq -2.0$ are $0.002 M_{\odot}$ or smaller. An upper limit to the mass of the mixed zone may be determined from solar observations. Helioseismology clearly shows that diffusion does occur in the Sun (Christensen-Dalsgaard, Proffitt, & Thompson 1993; Basu, Pinsonneault, & Bahcall 2000). The mass of the convection zone in the Sun is $M_{CZ} = 0.02 M_{\odot}$. As diffusion is not inhibited in the Sun, this suggests that the mechanism which inhibits diffusion only acts in the very outermost layers of a star (ie: for $M > 0.98 M_{\odot}$). Combined with the estimate for the minimum mass of the mixed zone given above, it appears that the mass of the mixed zone at the surface of hot metal-poor stars is in the range $M_{mix} \simeq 0.005 - 0.02 M_{\odot}$.

To determine what effects inhibiting diffusion in the outer layers of a star has on the observed properties of the models, the diffusion subroutine in our code was altered so that diffusion was shut off in the outer layers of the star. This was accomplished by setting the diffusion coefficients to zero when $M > M_* - M_{mix}$, where M_* is the total mass of the star. The diffusion coefficients were ramped from zero, up to their standard value in the region $M_* - M_{mix} > M > M_* - M_{ramp}$. For these test runs, we used $M_{mix} = 0.005 M_{\odot}$ and $M_{ramp} = 0.01 M_{\odot}$. The results of a sample calculation are shown in Figure 5, which shows the evolution in the effective temperature-luminosity plane. We see that when diffusion is inhibited in the outer layers of the model, the predicted temperatures of the models are similar to models evolved without diffusion. The primary reason diffusion models are cooler than non-diffusion models is that diffusion of helium out of the envelope increases the envelope opacity, which increases the model radius and hence, decreases the effective temperature. Thus, when diffusion is inhibited in the outer layers, the effective temperature of the models resembles the non-diffusion models.

The model in which diffusion was inhibited at the surface had a similar lifetime to the full diffusion model. This is because diffusion was not inhibited in the deep interior of the model. Helium diffused into the core (displacing the hydrogen) which leads to a shorter main sequence lifetime

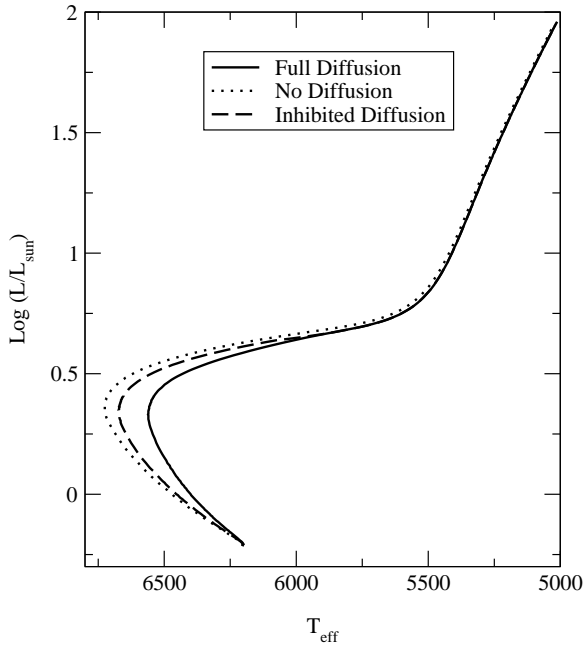


Fig. 5.— The evolution of models with full diffusion, no diffusion, and diffusion which has been inhibited in the outer layers of the star. All models had a mass of $M = 0.80 M_{\odot}$, an initial iron abundance of $[\text{Fe}/\text{H}] = -1.9$ and a mixing length of $\alpha = 1.75$.

compared to non-diffusion models. Such tracks by themselves, however, may provide a misleading guide to the impact of diffusion on cluster age estimates. To determine globular cluster ages one compares isochrones to observations. Diffusion will change the shape of the isochrones in a different way than it changes the shape of individual tracks because models with different masses experience different degrees of diffusion.

To explore the consequences this modification of diffusion has on age determinations, isochrones were calculated based upon the no diffusion models, and models in which diffusion was inhibited in the outer layers. These isochrones are compared to the full diffusion isochrones in Figure 6. The isochrone in which diffusion has been inhibited falls half-way between the isochrone with full diffusion, and the isochrone with no diffusion. If $M_V(\text{TO})$ is used as an age indicator, then ages determined using isochrones in which diffusion has been inhibited will be 4% larger ages derived from the full diffusion isochrones, and 4% smaller than

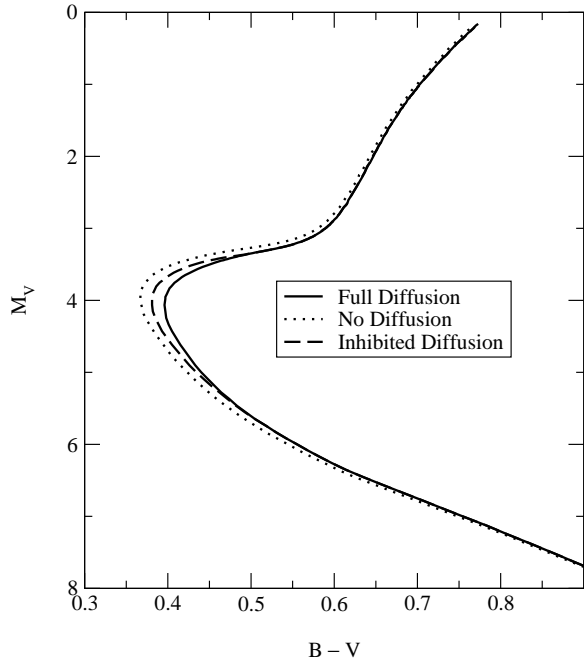


Fig. 6.— Isochrones with an age of 13 Gyr, an initial iron abundance of $[\text{Fe}/\text{H}] = -1.9$ and a mixing length of $\alpha = 1.75$.

ages derived using the no diffusion isochrones.

If diffusion is inhibited near the surface of metal-poor stars (likely by rotation induced mixing), one naturally wonders if diffusion occurs in the deep interior of metal-poor stars. Perhaps the rotation induced mixing suppress the diffusion throughout the entire star. At the present time, there is no clear answer as to whether or not diffusion is occurring in the deep interior of metal-poor stars. A definitive answer will likely have to await observations from stellar seismology, which will probe the interior structure of metal-poor stars and allow one to test the interior properties of theoretical models.

This study has shown that diffusion is inhibited in the surface layers of metal-poor stars. Stellar models and isochrones which include the full effects of diffusion are in error, and should not be used for comparing to observational data. Our calculations in which diffusion is inhibited near the surface of the star are admittedly ad-hoc. However, as helioseismology has shown that diffusion is occurring in the interior of the Sun, we believe it is likely that diffusion is also occurring in the

interiors of metal-poor stars. The obvious difference between the Sun and the metal-poor turn-off stars, is that the surface convection zone is much larger in the Sun. Theoretical calculations of rotation induced mixing have shown that this mixing is most effective in the outer layers of a star (e.g. Chaboyer, Demarque, & Pinsonneault 1995; Brun, Turck-Chièze, & Zahn 1999). The fact that diffusion is occurring in the interior of the Sun makes us believe that diffusion is only being inhibited in the outermost layers of stars. For this reason, we prefer the use of stellar models and isochrones in which diffusion operates in the interior of the model (but not in the outer layers) to models which do not include diffusion. Given that diffusion is occurring in the Sun, stellar models and isochrones which include diffusion are appropriate for solar-type stars. The model we have presented for inhibiting diffusion in the surface layers of stars allows one to use a set of isochrones calculated using the same assumptions for both metal-poor and solar-type stars.

5. Summary

A large number of stellar evolution models which include the effects of helium and heavy element diffusion were constructed. The amount of diffusion of iron out of the surface convection zone is a strong function of the mass and age of a star. As a result, the models predicted that the $[\text{Fe}/\text{H}]$ abundance measured in the turn-off stars in the globular cluster NGC 6397 should be more than 0.28 dex lower than the $[\text{Fe}/\text{H}]$ measured in the giant branch stars. In contrast, observations by Gratton et al. (2001) demonstrate that the turn-off and giant branch stars have identical values of $[\text{Fe}/\text{H}]$ indicating that uninhibited metal diffusion does not occur in the surface layers of metal-poor stars. Based upon this observed fact and the physical principals underlying diffusion processes, we estimate that the minimum mass of the region where diffusion is inhibited near the surface of metal-poor stars to be $M_{\text{mix}} \gtrsim 0.005 M_{\odot}$. Models and isochrones in which diffusion was inhibited in the outer layers were calculated and compared to full diffusion isochrones, and isochrones without diffusion. The isochrones in which diffusion has been inhibited have properties which lie half-way between the full diffusion isochrones, and the no diffusion isochrones. As a consequence, globular

cluster age estimates which use $M_V(\text{TO})$ as their age indicator, and which are based upon models which include the full effects of diffusion need to be revised upward by 4%. Helioseismic observations clearly show that diffusion is occurring in the Sun, which suggests that diffusion operates in most regions of a star. Our models which include diffusion which is inhibited in the outer layers of the star yield globular cluster ages which are 4% smaller than models which do not include diffusion when $M_V(\text{TO})$ is used as an age indicator.

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